Detecting and Switching skyrmion coupling using Resonant Ultrasound Spectroscopy

Boris Maiorov

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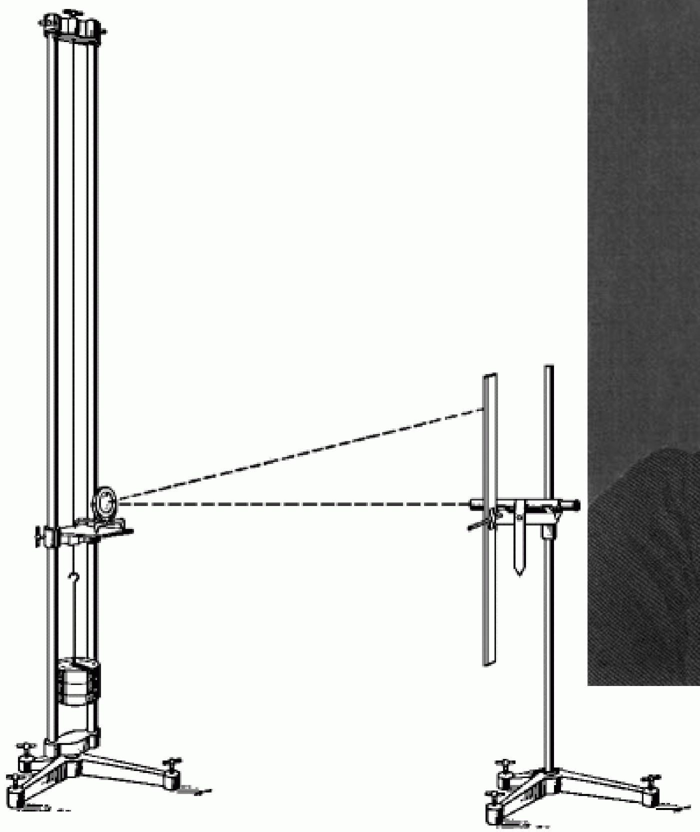
Bad memories from elastic experiments

- Young's modulus was the first experiment I '**did**' when as undergrad in Bariloche

$$E \equiv \frac{\sigma(\varepsilon)}{\varepsilon} = \frac{L_0 F}{A\,\Delta L}$$

- Young modulus measures the ratio of tensile stress and tensile strain
- Young also made great advances deciphering Egyptian hieroglyphs
- Developed the Young temperament method to **tune instruments**
- etc



Sir Thomas Young
(13 June 1773 – 10 May 1829)

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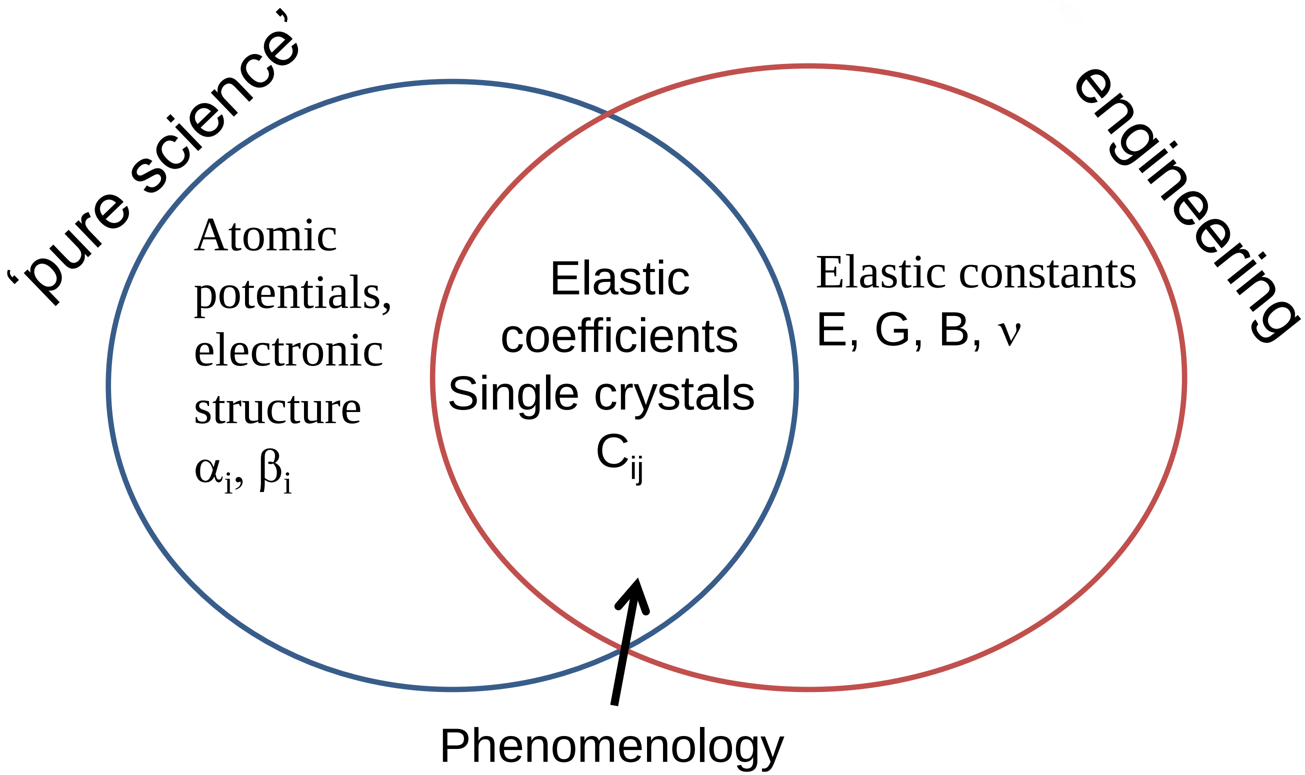
Why elasticity?

Elastic moduli are fundamental thermodynamic susceptibilities that connect directly to thermodynamics, electronic structure and also gives important information about mechanical properties.

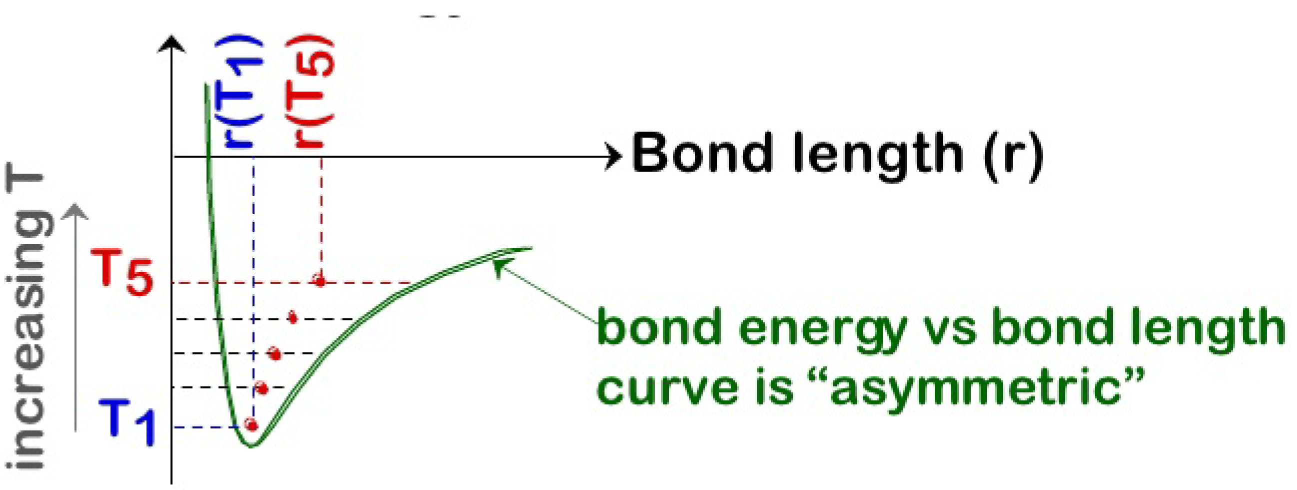


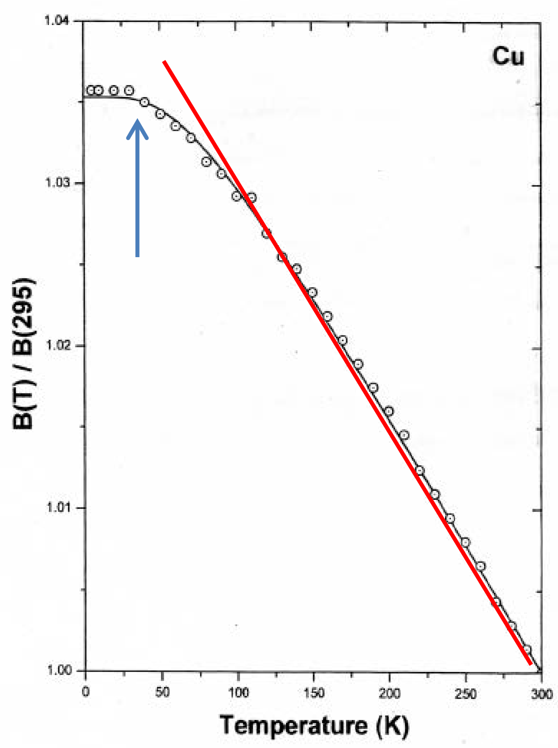
Elastic constants same information as sound velocity

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

Elastic properties dependend on interatomic potential

- Thermal expansion (increase volume with increasing temperature)
- Thermal softening (decrease stiffness with increasing temperature





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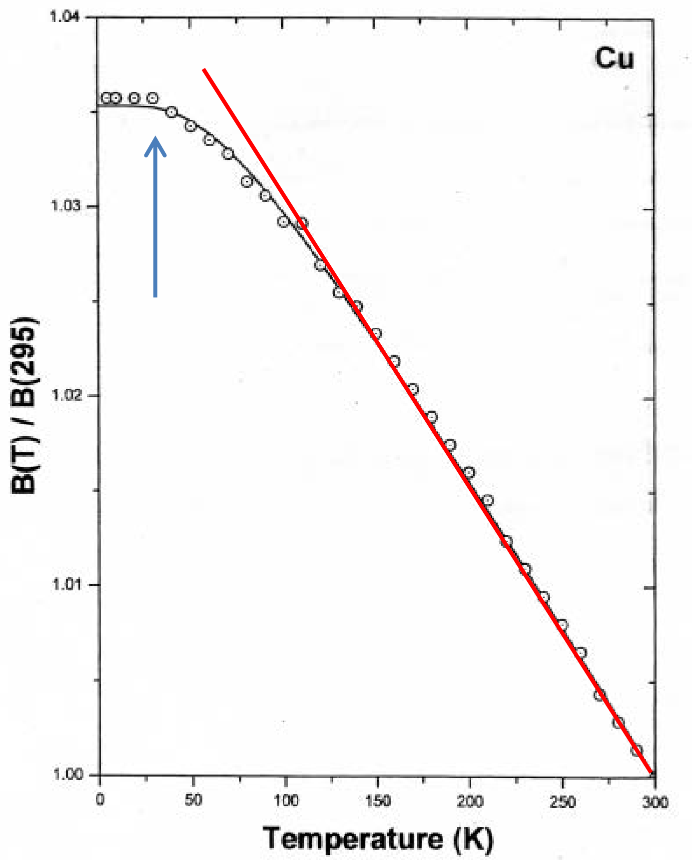
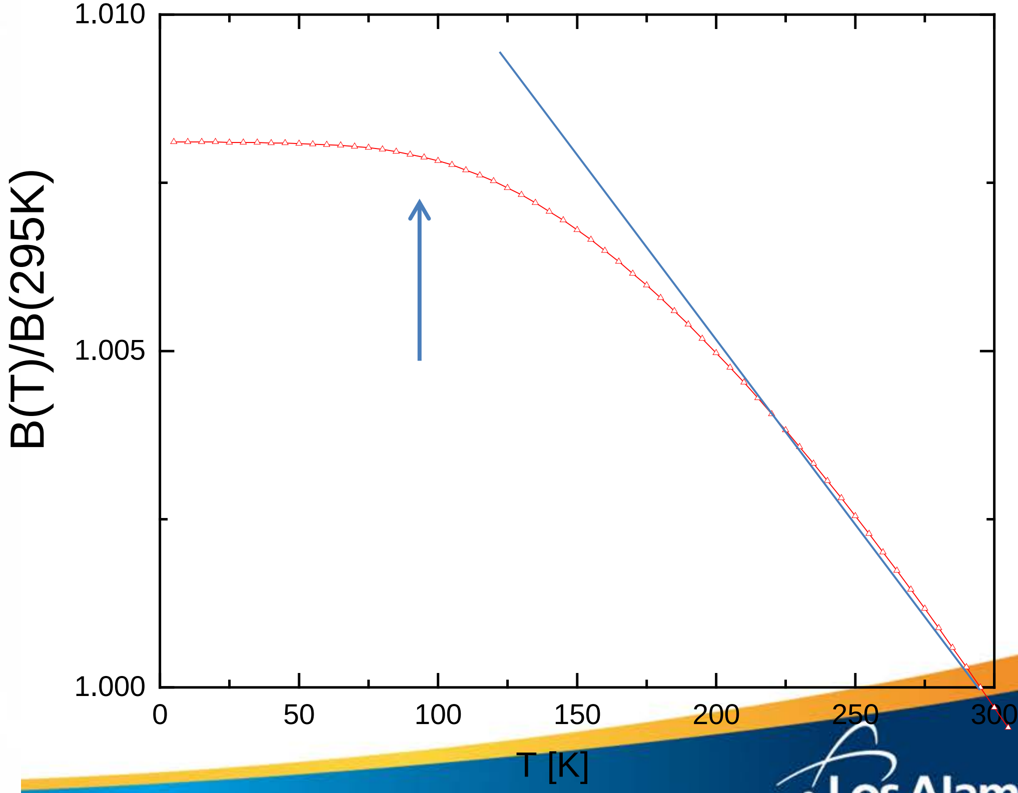
Softening with increasing temperature in metals

Copper



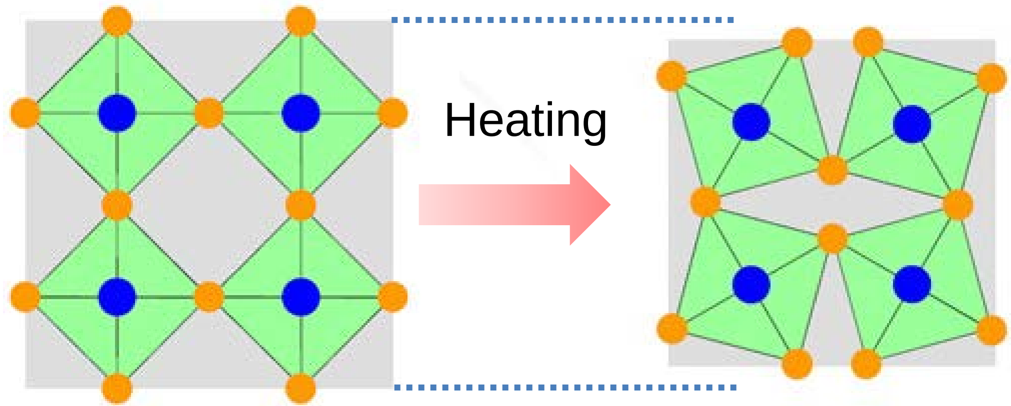
Beryllium

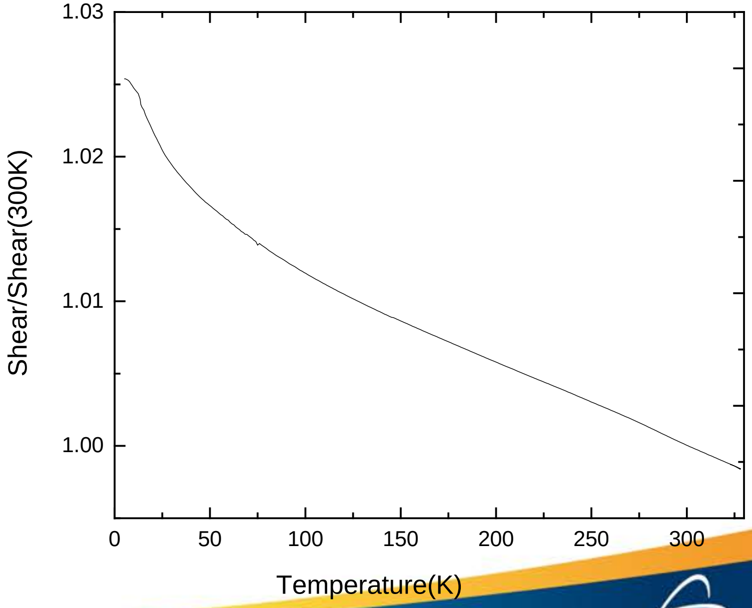
- Low Grüneisen parameter (from slope)
- High Debye temp ~1400K from leveling



Elastic properties reveal internal degree of freedom in shrinking materials

- ScF_3 negative thermal expansion
- Rhomboid rotation
- Elastic moduli decreases with increasing temperature





Study of unconventional superconductivity

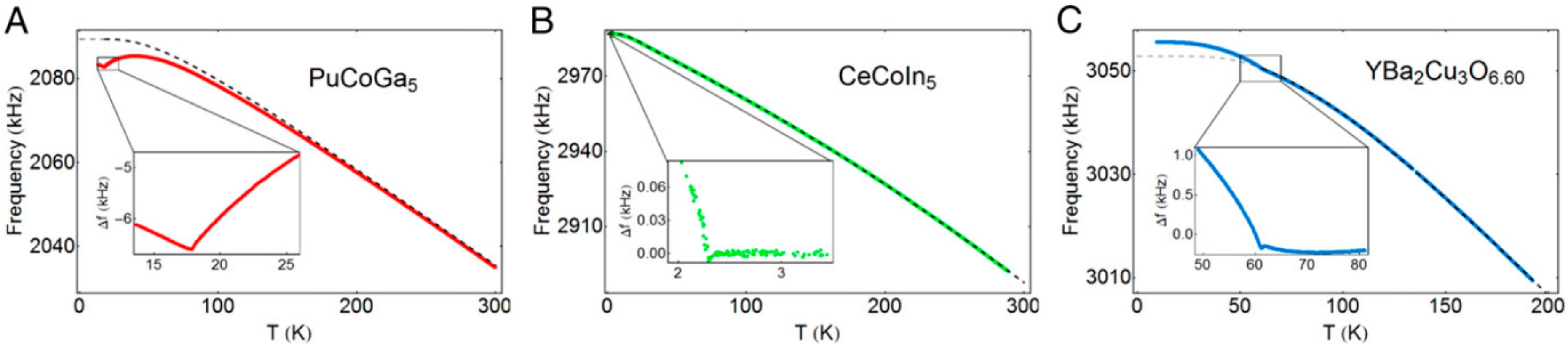
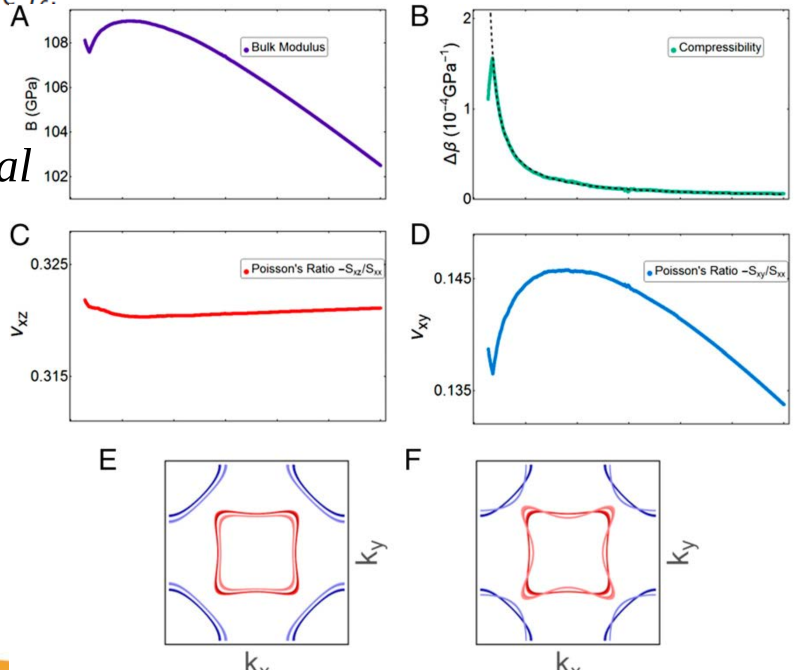


Fig. 3. Compressional resonances in three unconventional superconductors. Resonance modes dominated by the scalar moduli are shown for (*A*) PuCoGa$_5$, (*B*) CeCoIn$_5$, and (*C*) YBa$_2$Cu$_3$O$_{6.60}$. Although all three materials show a discontinuity at T_c and all stiffen immediately below T_c, only PuCoGa$_5$ shows the dramatic softening above T_c.

B. Ramshaw *et al* PNAS (2015)

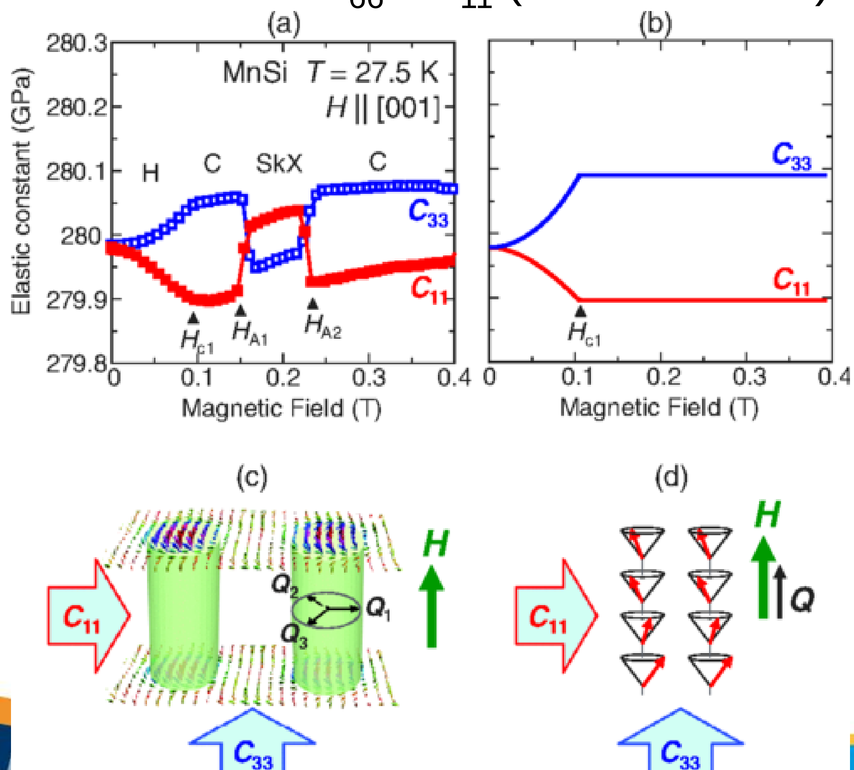


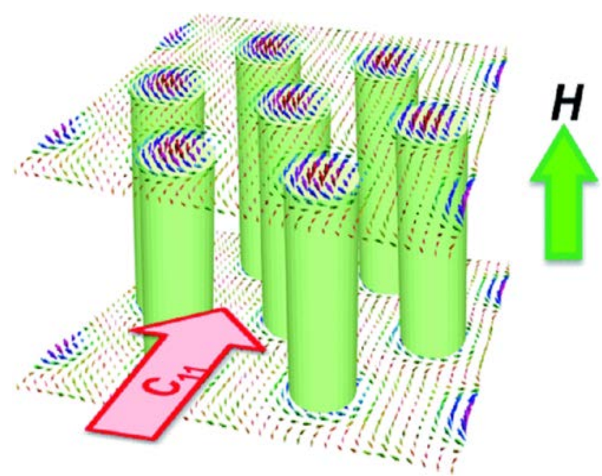
Bulk modulus softens dramatically before T_c—evidence for fluctuations of the plutonium valence as opposed to magnetic fluctuations associated with the suppression of magnetic order.

In-plane Poisson's ratio shows anisotropy in softening at the transition

Ultrasound used to detect and study skyrmion phase

- Skyrmion lattice can be detected by the changes in elastic constants
- Hardening perpendicular to applied field (C_{11}), while softening along H (C_{33})
- Inversion of the C_{11} and C_{33} is caused by the change of propagation vector orientation
- Values on compression (C_{11}) of Skyrmions consistent with vortex lattice compression
- Shear modulus C_{66} ~C_{11} (not measured) but for vortex ¼C_{11}



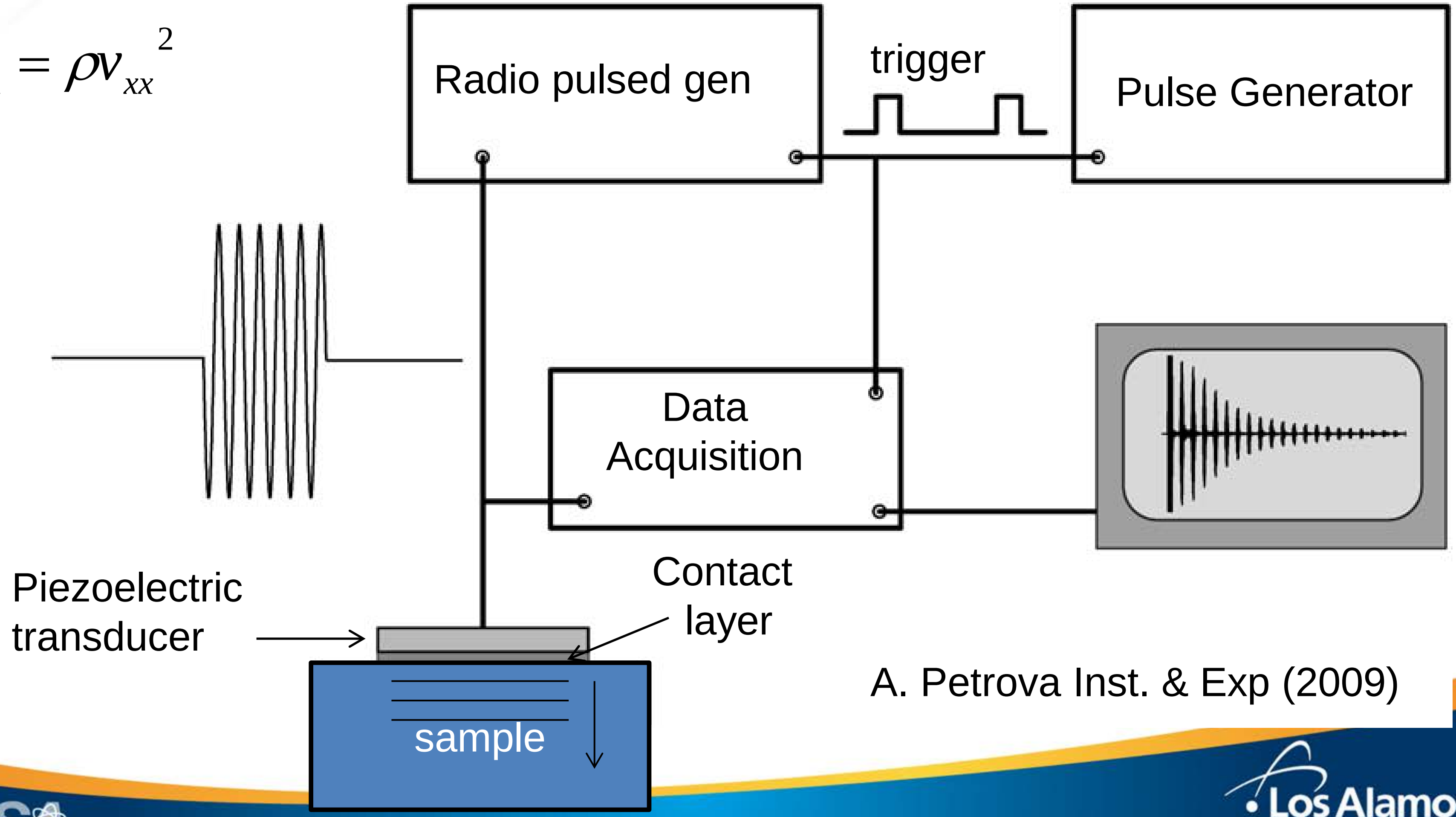


Nii *et al* PRL 113 (2014)

Pulse echo technique

- Measures sound velocity (v_{ii}) and attenuation
- One sample per C_{ij}
- Easy to analyze, fast (MHz), need 'glue'

$$C_{11} = \rho v_{xx}^{2}$$



A. Petrova Inst. & Exp (2009)

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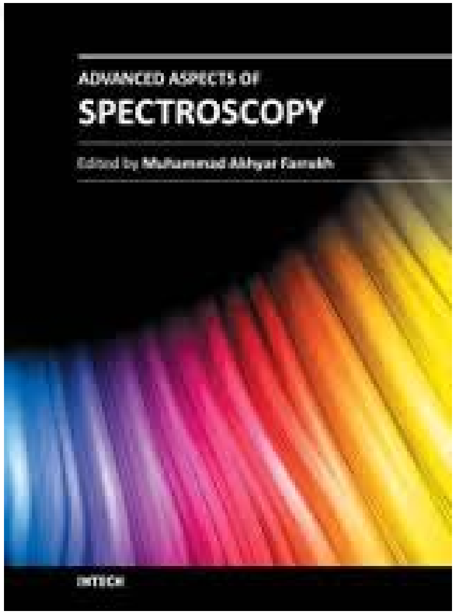
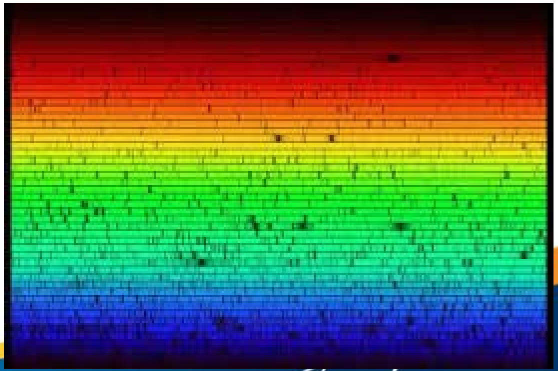
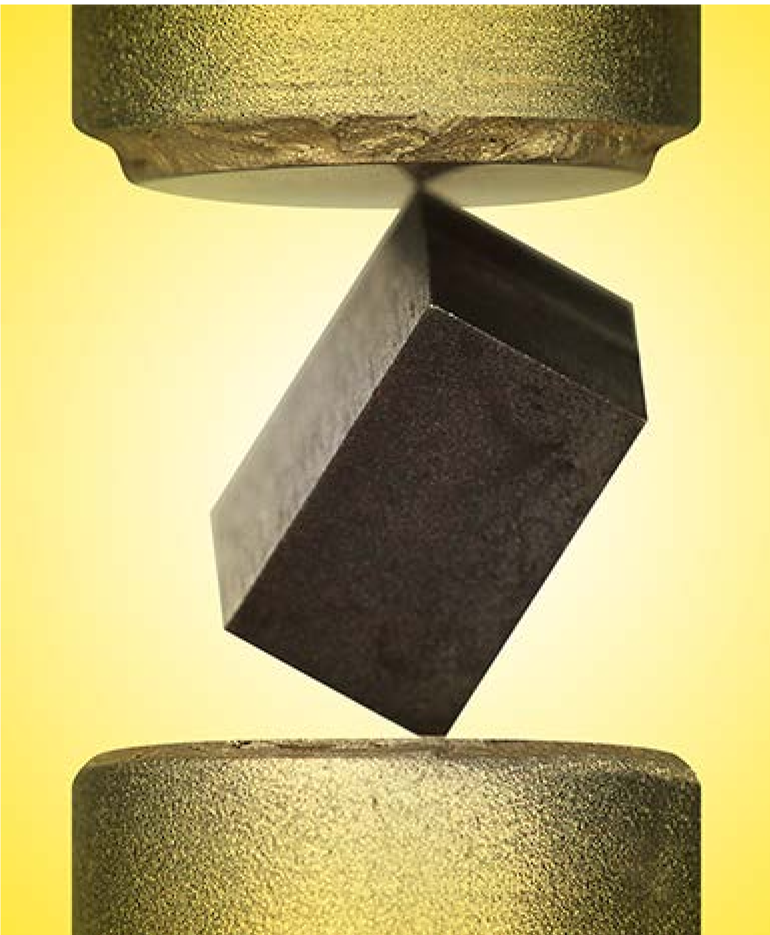
Resonant Ultrasound Spectroscopy (RUS)

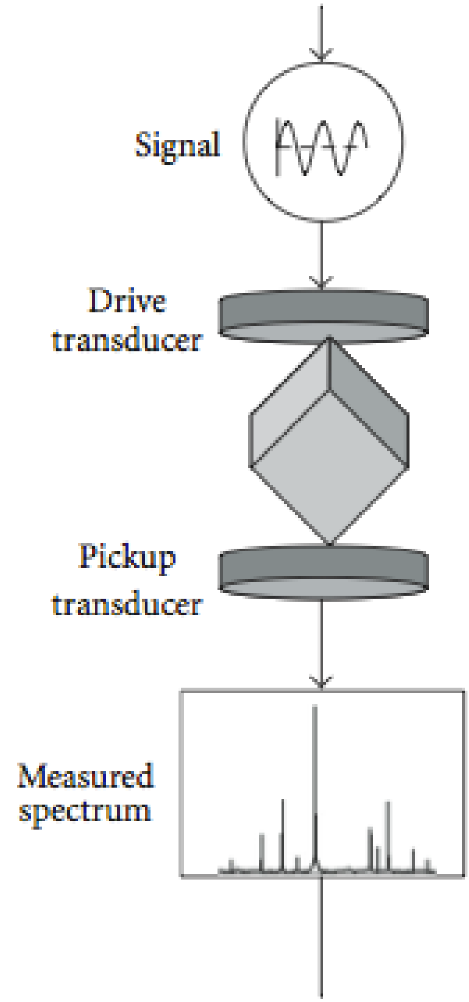




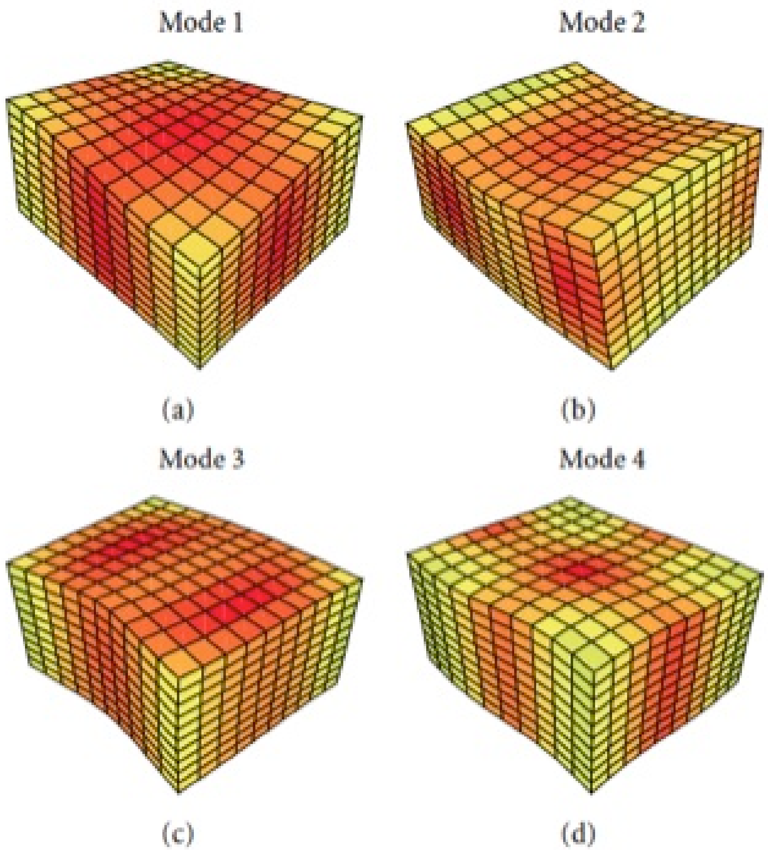
Resonant Ultrasound Spectroscopy

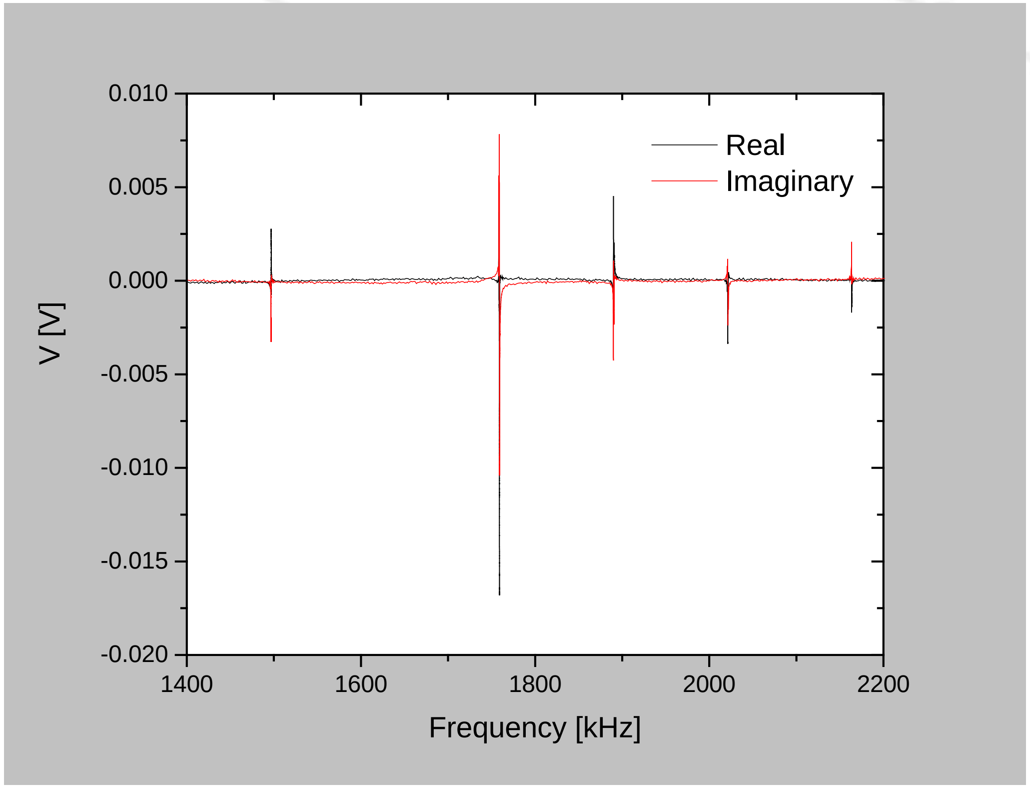
- Measures resonances in normal modes





...to measure normal modes that look like this....





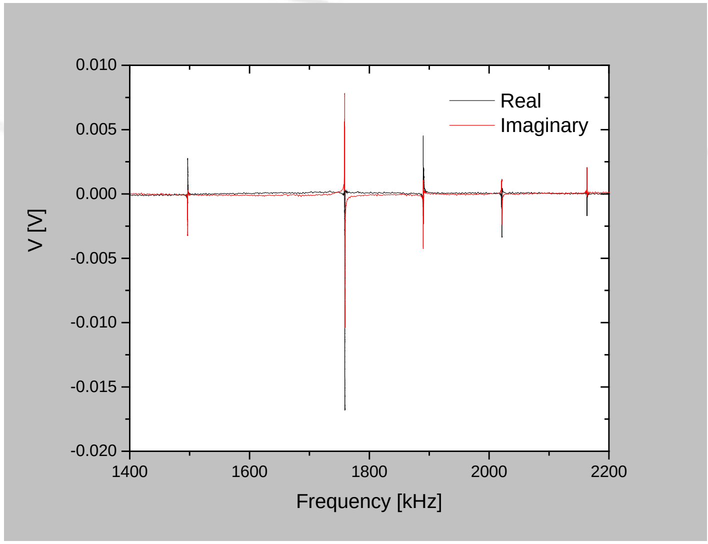
Using resonance positions + computational model

Elastic constants *Cij*

- Wavelengths ~ sub sample size
- Depends known geometry & symmetry
- Calculate spectrum is 'easy' (Forward problem)
- Obtain C_{ij} from spectrum (Inverse problem) not so easy

Full elastic tensor obtained from one spectrum

- Peaks are indexed
- Calculation of elastic constants involves crystal symmetry, sample dimensions and mass *
- Find values for C_{ij} that minimizes Error(f_m-f_{calc})
- Overdetermined solution (~10-30 frequecies)
- Each frequency has a particular dependence with C_{ij}
- Calculation of elastic constants involves crystal symmetry, sample dimensions and mass
- Over determined solution



Isotropic : 2 $\quad B = (C_{11} + 2C_{12})/3, G = (C_{11} - C_{12})/2 = C_{44}$

Cubic : 3 $\quad C_{11}, C_{12}, C_{44}$ $\qquad$ Cubic $\xrightarrow{H // \mathbf{c}}$ Tetragonal

Tetragonal : 6 $\quad C_{11}, C_{33}, C_{13}, C_{12}, C_{44}, C_{66}$

Orthorhomic : 9 $\quad C_{11}, C_{22}, C_{33}, C_{13}, C_{23}, C_{12}, C_{44}, C_{55}, C_{66}$

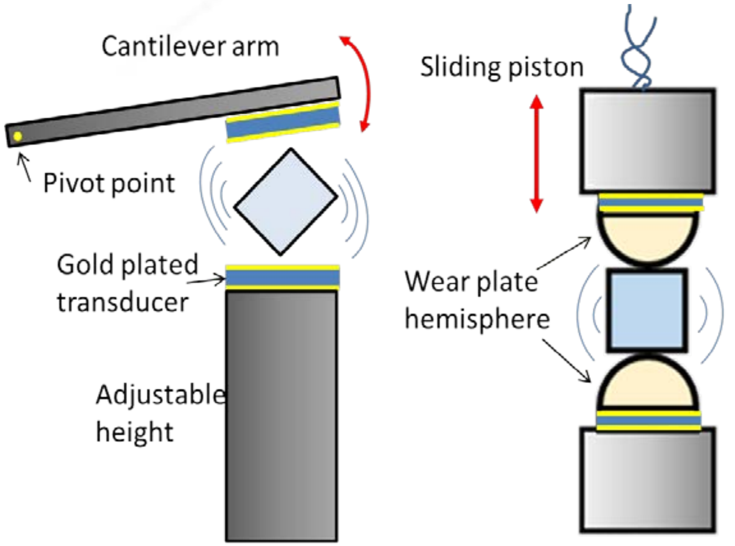
n	Fcal	dF/d(Cij)					
		C11	C33	C23	C12	C44	C66
1	1.059120	0.01	0.01	-0.01	0.00	0.36	0.62
2	1.189275	0.03	0.00	0.00	-0.01	0.93	0.04
3	1.387761	1.08	0.01	-0.01	-0.25	0.17	0.00
4	1.424889	0.83	0.23	-0.19	-0.05	0.02	0.16
5	1.494300	0.07	0.02	-0.02	0.00	0.00	0.93
6	1.514623	0.74	0.36	-0.24	-0.03	0.04	0.13
7	1.535049	0.08	0.02	-0.01	-0.02	0.92	0.00
8	1.571518	0.09	0.03	-0.01	-0.02	0.91	0.00
9	1.602741	0.70	0.08	-0.14	0.09	0.27	0.00
10	1.638797	1.31	0.05	-0.04	-0.32	0.00	0.00
11	1.690252	0.91	0.45	-0.28	-0.08	0.00	0.00
12	1.710295	0.16	0.66	-0.05	-0.03	0.20	0.06

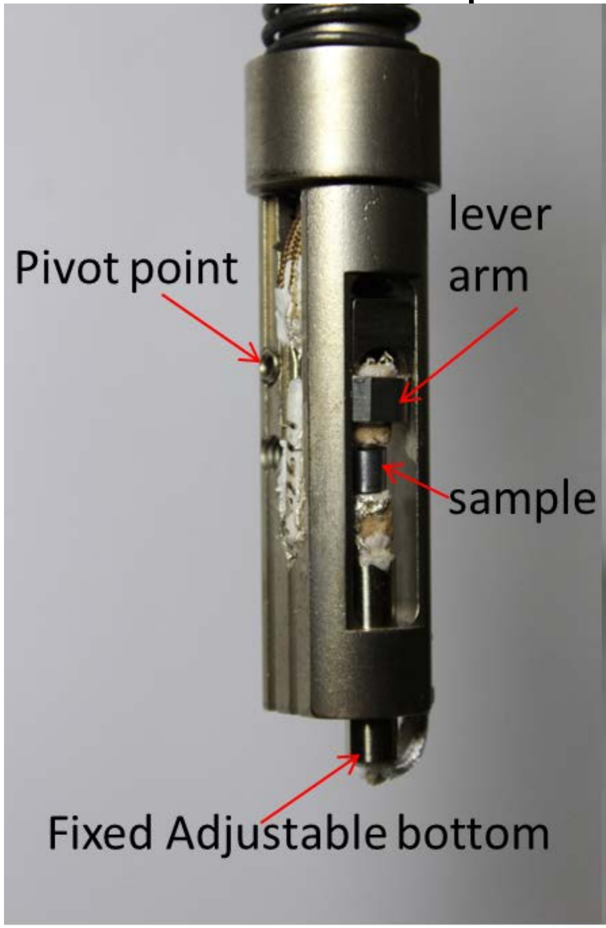
Many times is easier to track a frequency rather than solving C_{ij} for each spectrum

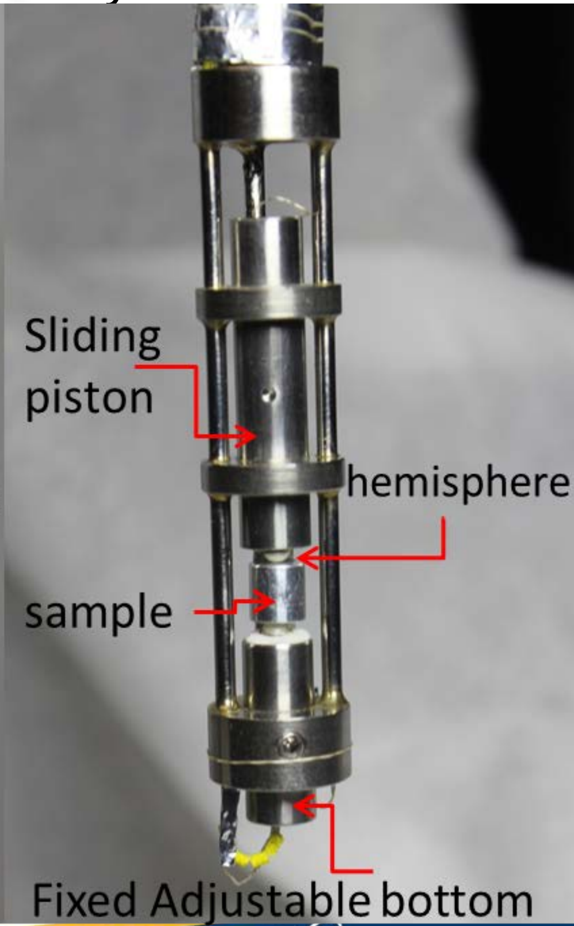
$C_{ij} \sim f^{2}$

RUS can be used from cryogenic to very high temperatures

- New acoustically dead composite materials developed
- Wear plates for longer transducer life and sample stability

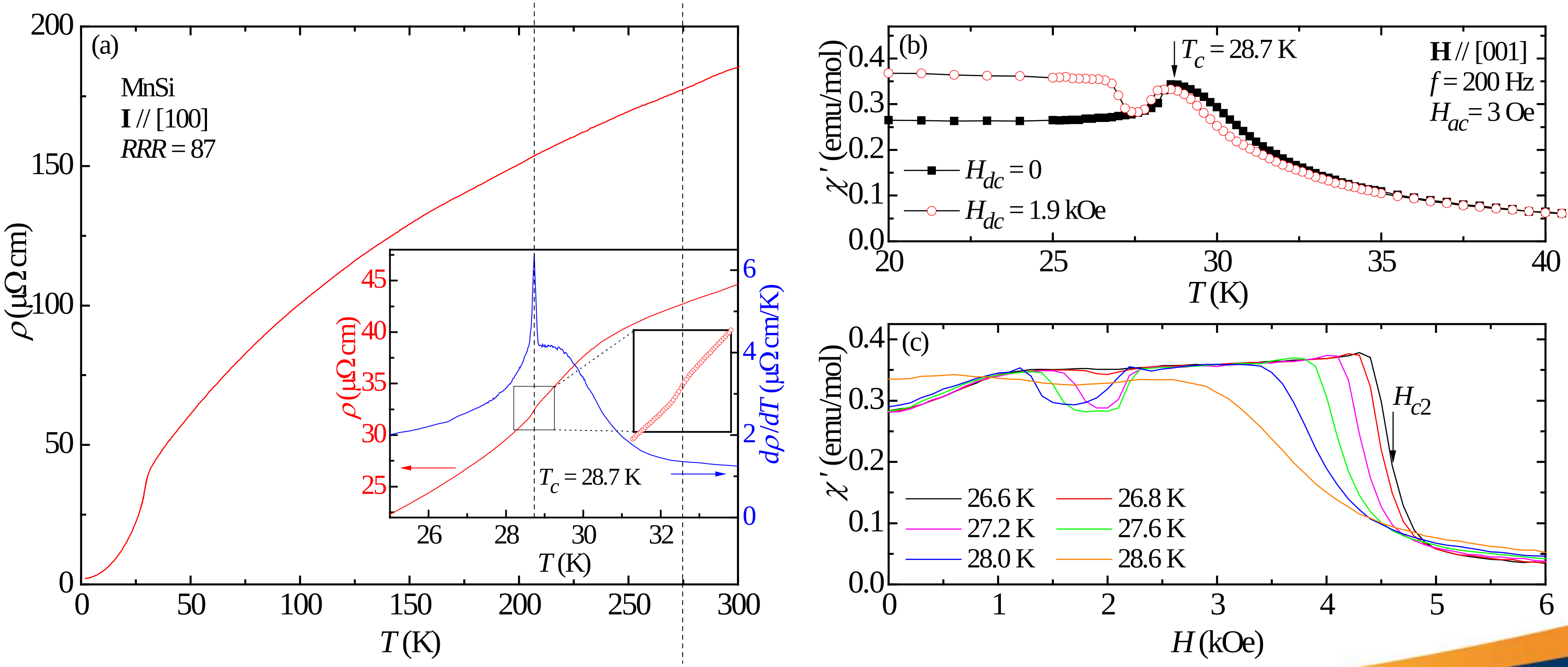






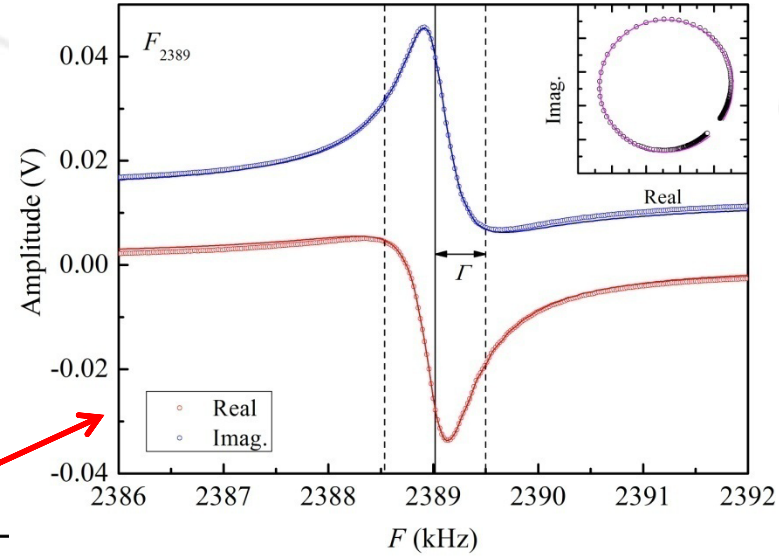
Transport and susceptibility measurement show skyrmion phase

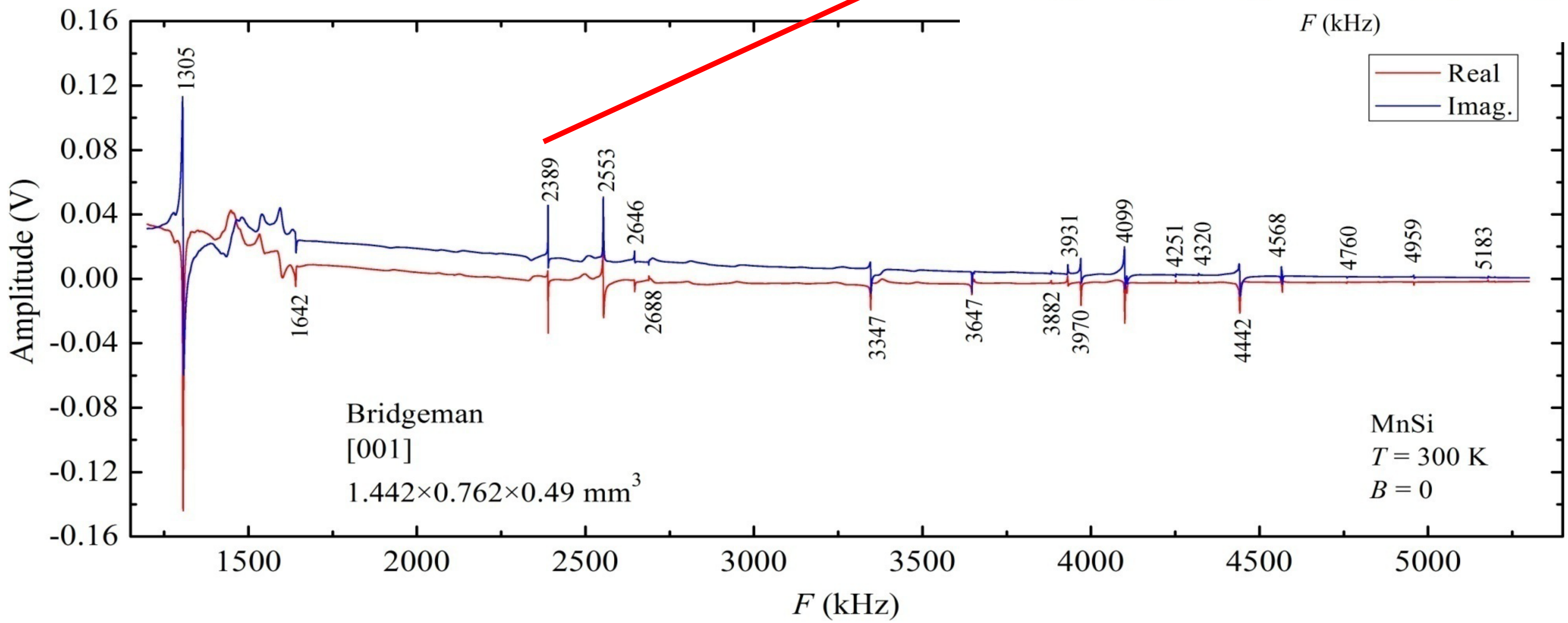
- Crystal grown by Bridgeman method
- Transport and susceptibility show T_c and skyrmion phase
- THE shows important differences with respect to literature



Room Temperature RUS spectrum for MnSi

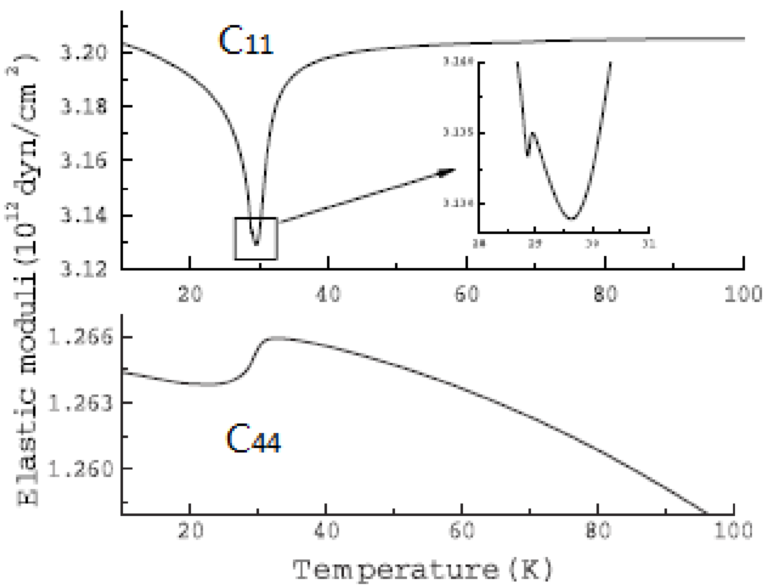
- Resonant frequency $\propto C_{ij}^{1/2}$
- $\Gamma \propto Q^{-1}$ sound attenuation/absorption
- Attenuation measured by RUS less sensitive to disorder

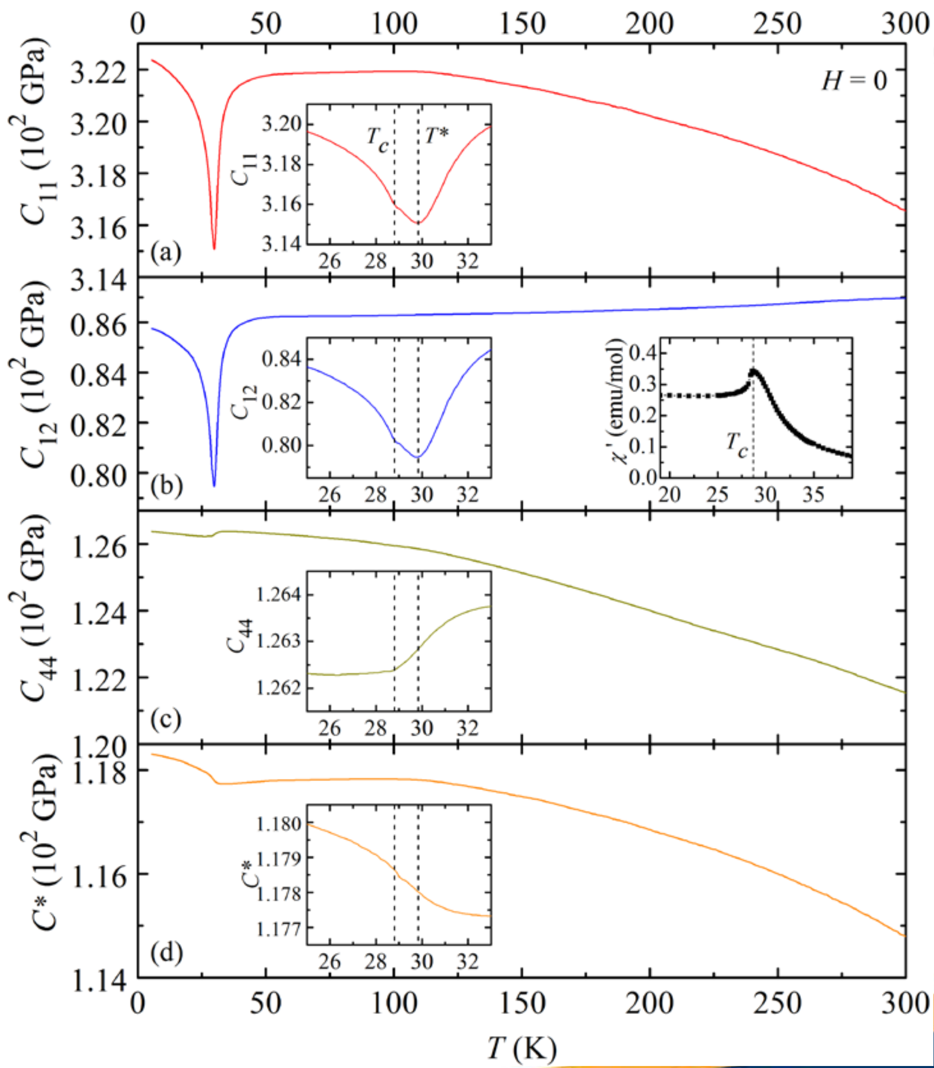




Full tensor calculation with cubic symmetry

- Clear feature in C_{11} and C_{12}, C_{44}
- Comparison with Pulse echo shows similar values and features
- For $T<T_c$, we can see clear evidence of broken symmetry as a consequence of conical phase





S. M.Stishov, PRB (2007)
A. E. Petrova, JPCM (2009)

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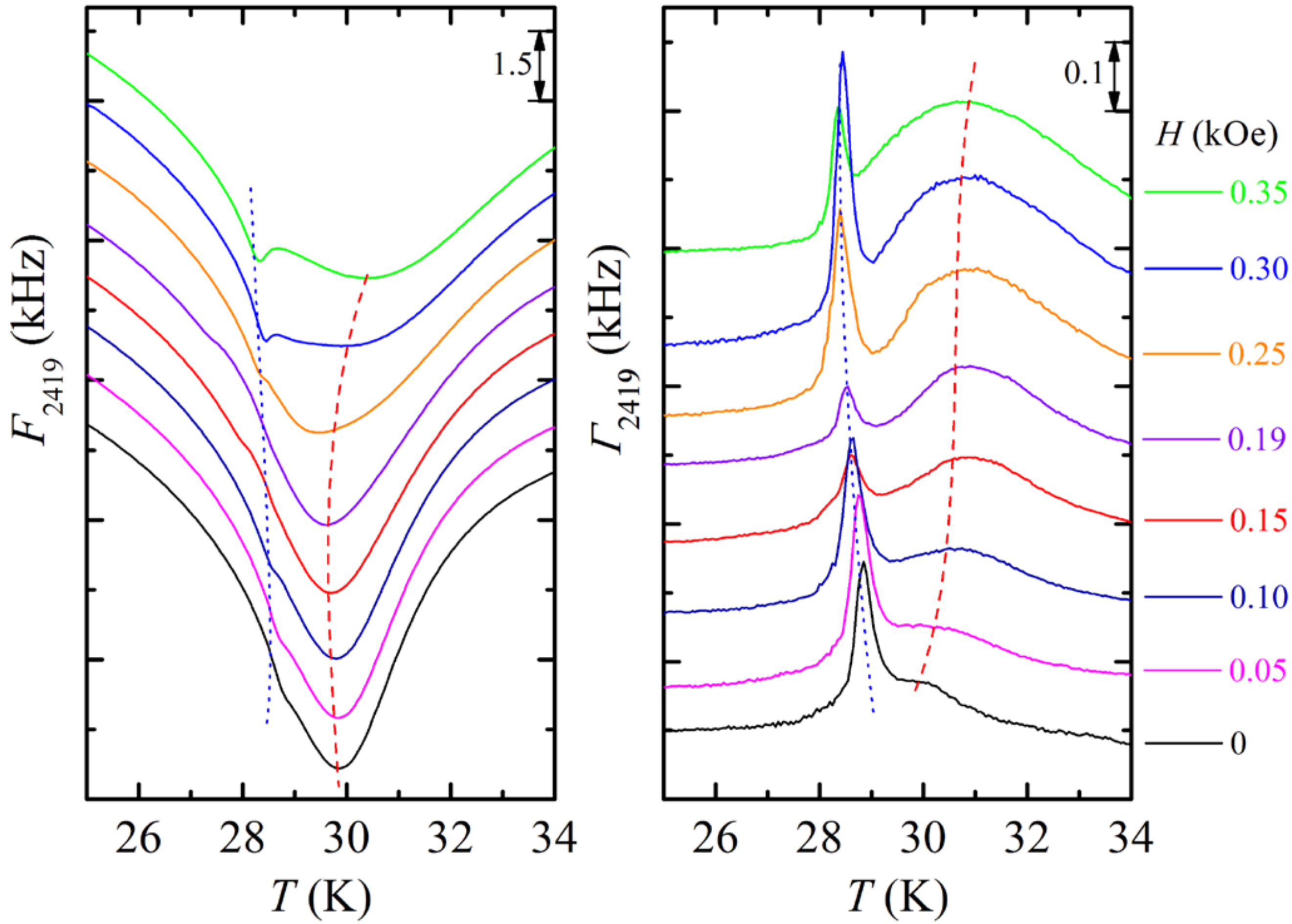
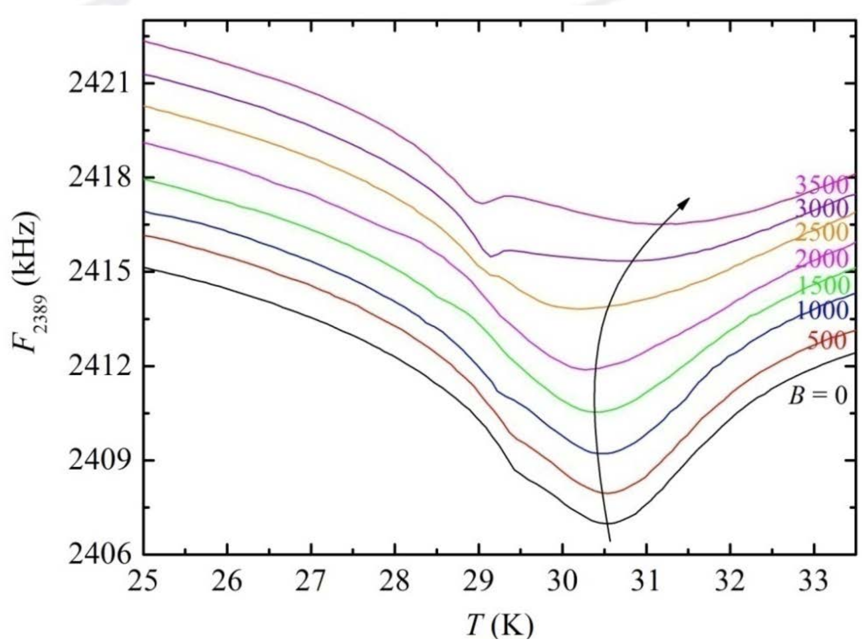
Frequency and attenuation change with temperature

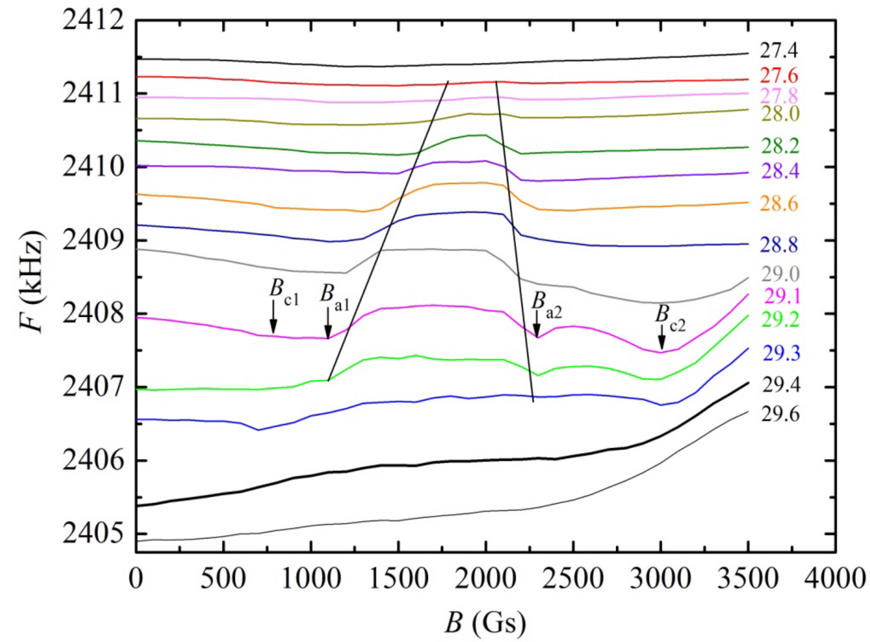
- Attenuation shows a broad maximum in dissipation at higher *T*
- Maximum in attenuation higher *T* than minimum in F
- Sharper maximum in attenuation at transition

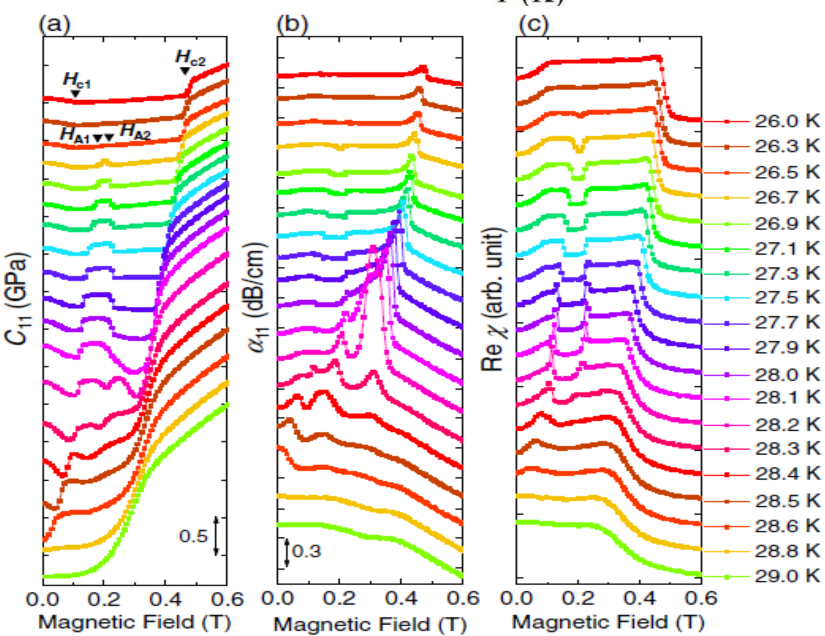
H||[100]



Resonance vs Field and Temperature







- Resonant frequencies field and temperature dependences capture changes in different magnetic phases

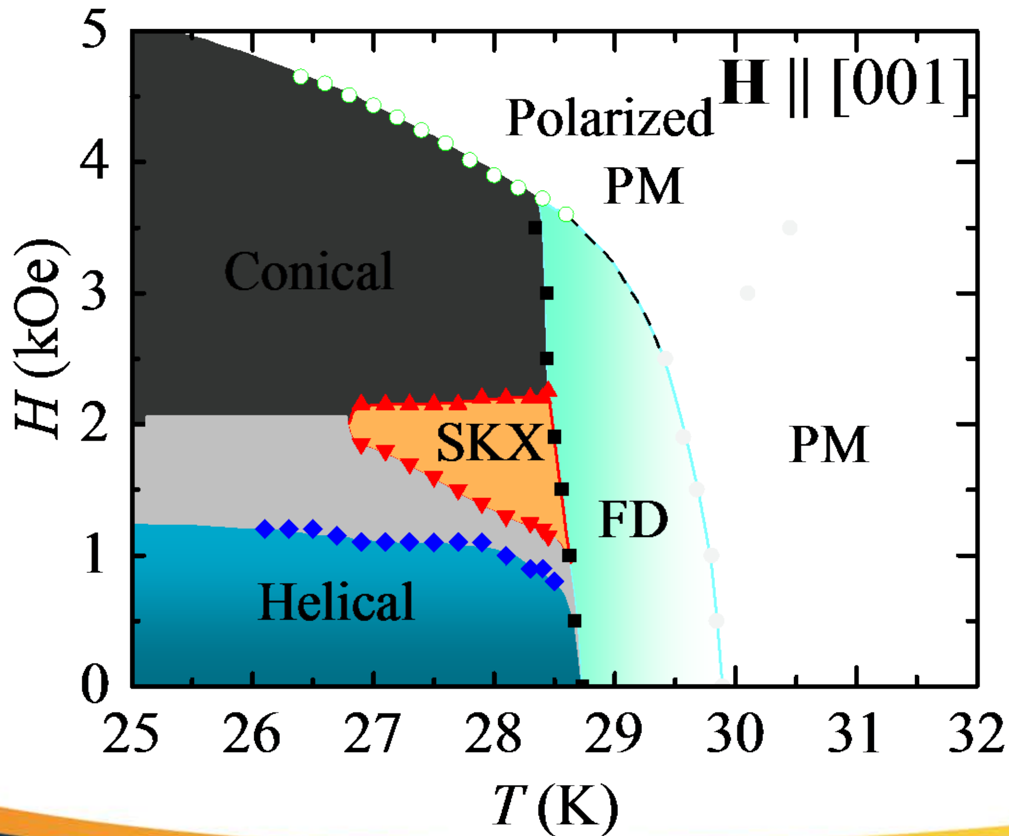
Similar results from pulse echo

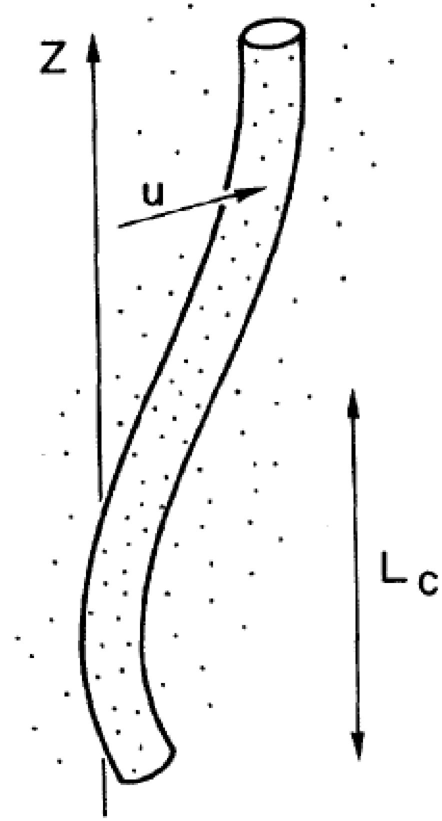
Y. Nii, PRL (2014)

al Security, LLC for the U.S. Department of Energy's NNSA

Full phase diagram obtained using RUS

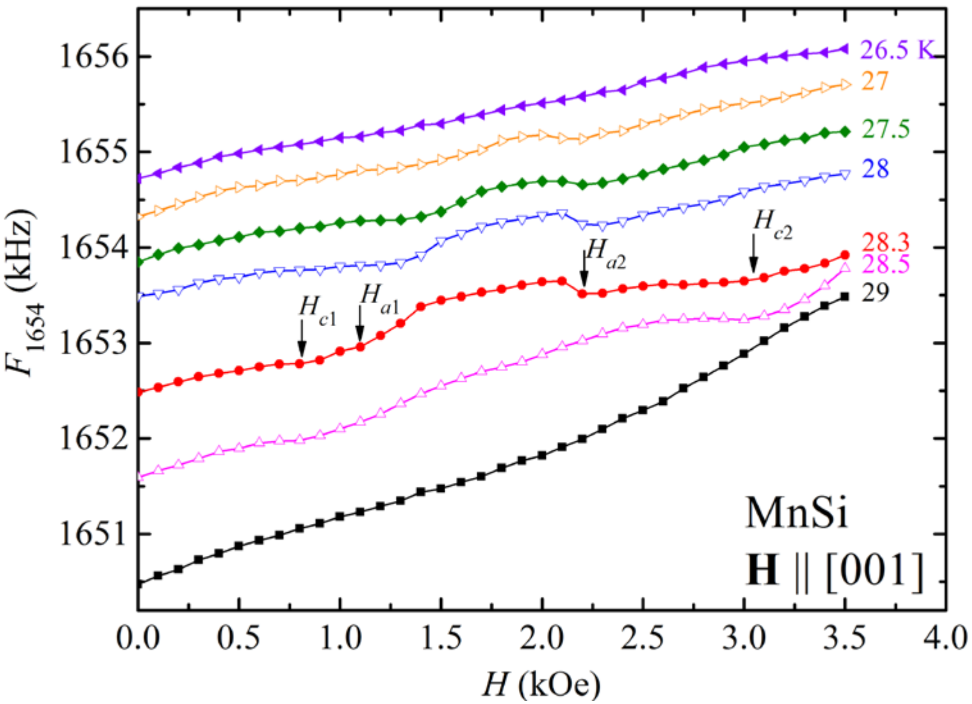
- RUS can be used to detect different magnetic phases
- However, more information can be obtained beyond detection and qualitative description
- Relate thermodynamic (stiffness) and dynamic (critical current) properties

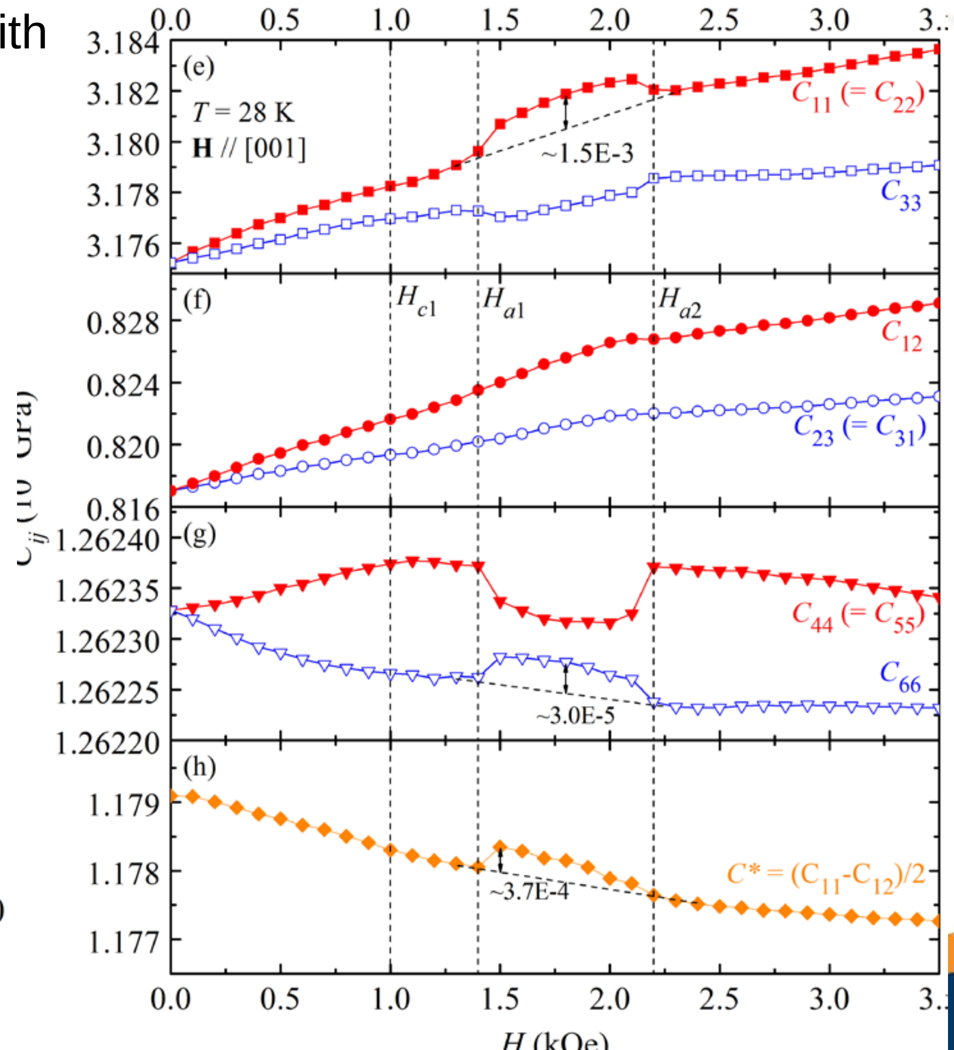




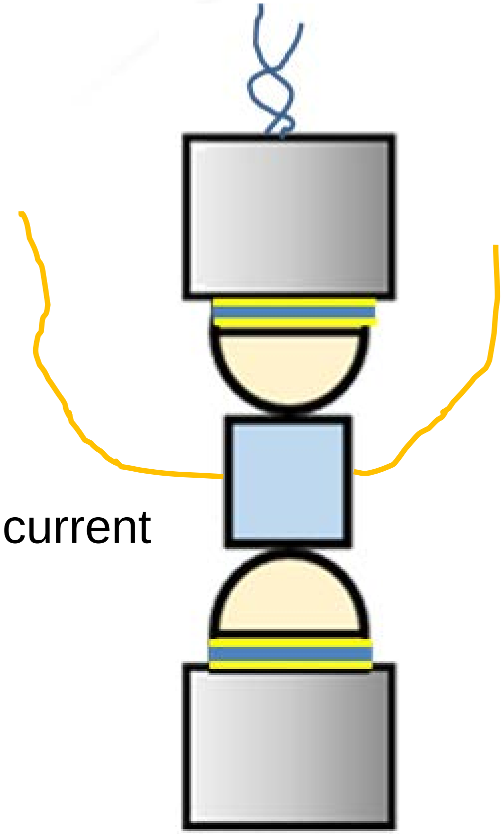
Complete elastic moduli of MnSi in SKX phase

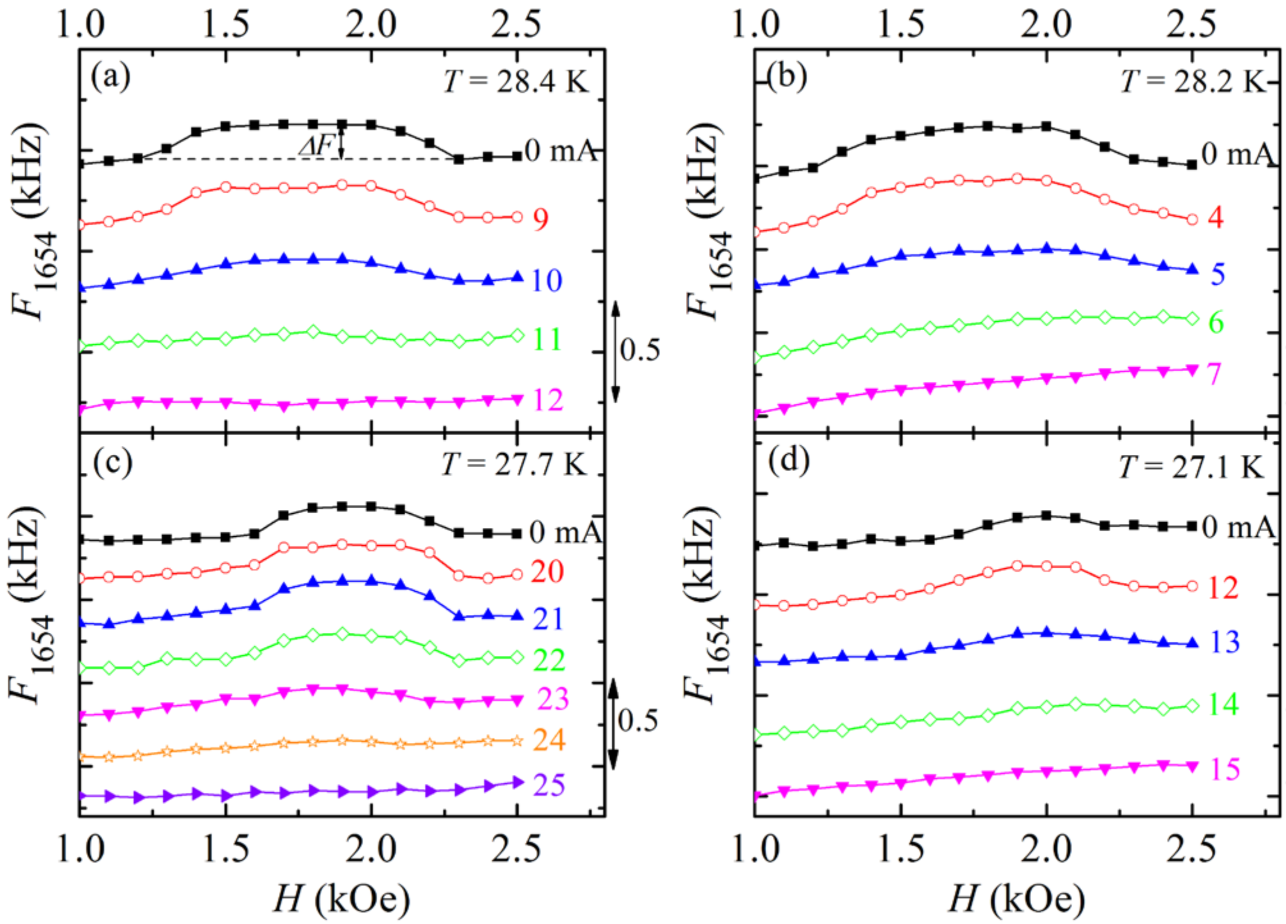
- Clear feature in frequency translated jump in C_{ij}
- Qualitative and quantitative agreement with pulse echo results
- Changes in $C_{11} >> C_{66}$
- $C^* \neq C_{66}$ (No hexagonal symmetry)





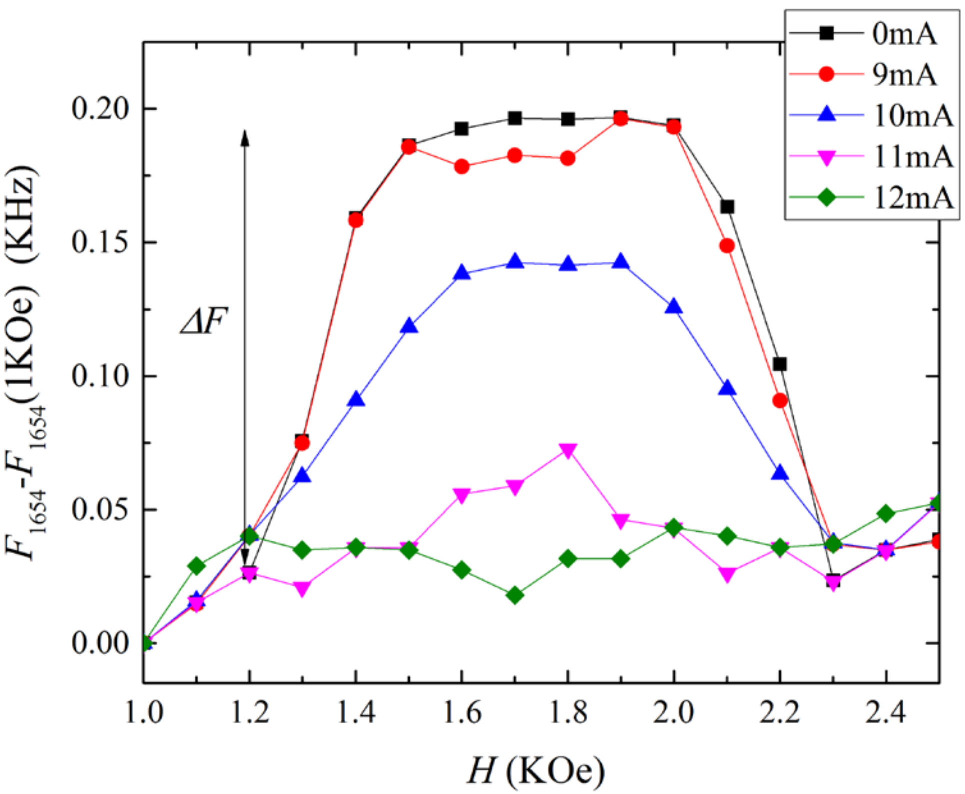
Current applied while maintaining resonance condition

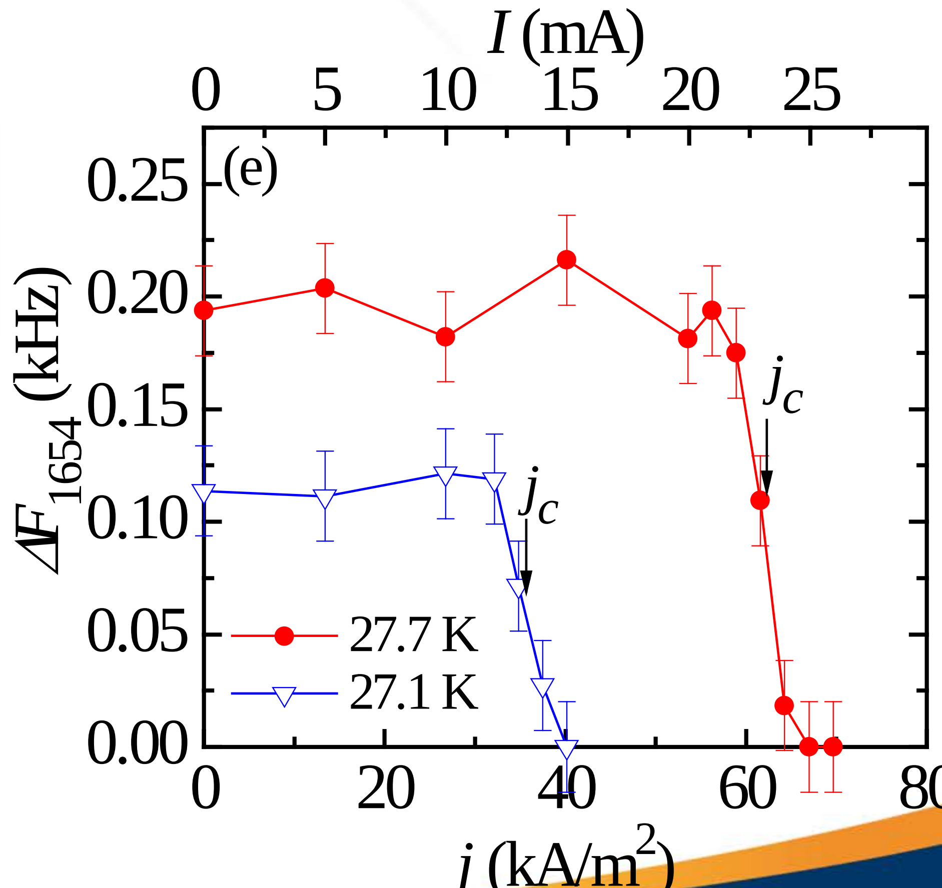




Jump in stiffness is lost for $j>j_c$

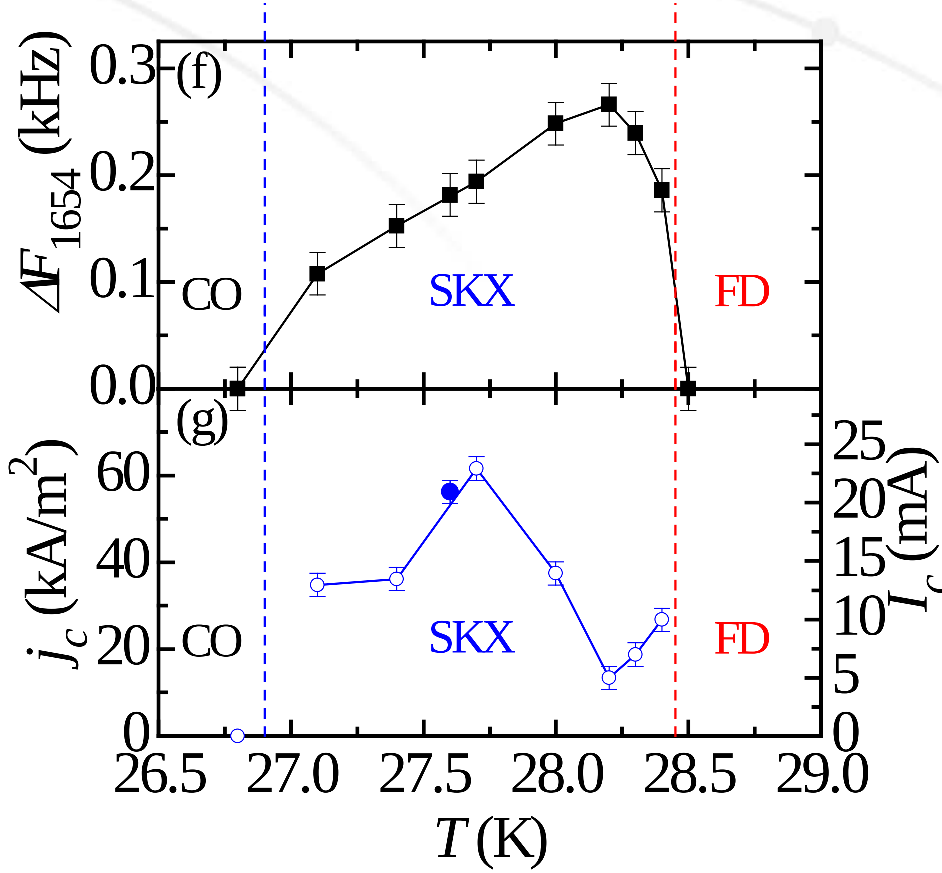
- Decoupling of skyrmions from ionic lattice
- Decoupling = depinning? (moving skyrmios)
- Smaller value found (20-60kA/m^2) than in Hall and Neutrons (1MA/m^2)

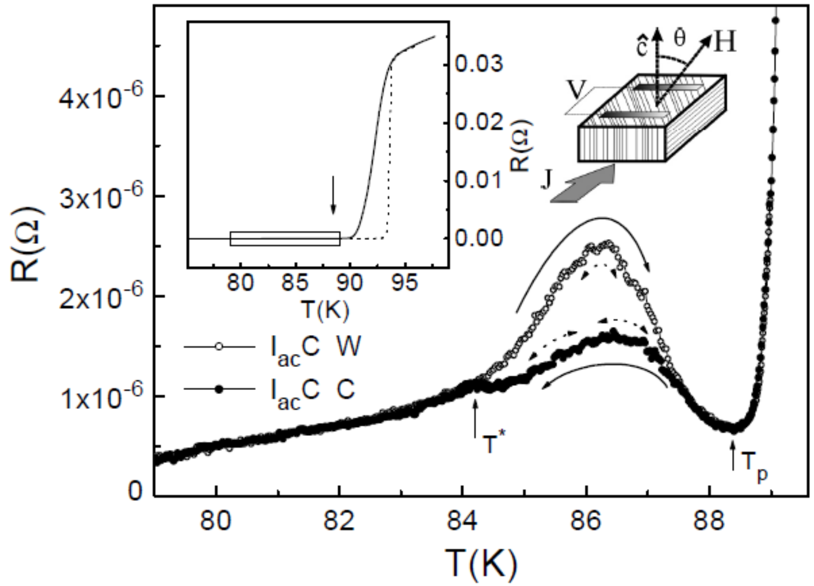




Influence of elasticity and temperature in j_c

- Ultrasonic excitation does not affect j_c
- No effect of heating
- Difference in detection or sample
- RRR similar but THE different
- Different *T* dependence than THE
- Abruptness can be explained as averaging





Peak effect in superconducting vortices
Valenzuela, Maiorov, et al PRB (2002)

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Summary and conclusions

- Skyrmion phase detected by RUS
- Attenuation gives insight to FD phase
- First full determination of complete elastic tensor in Skyrmion phase, $\Delta C_{11} >> \Delta C_{66}$
- Current induces decoupling to ionic lattice